The Electron Distributions in the Mars and Venus Upper Atmospheres

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ABSTRACT

Theoretical models of the Mars and Venus ionospheres are constructed and compared with the observed electron distributions in the upper atmospheres of these planets. It is found that a serious discrepancy exists between calculated and observed electron densities for all the Mariner flights if the presently accepted values of the solar extreme ultraviolet radiation are assumed to be the only ionization source. This result suggests the presence of a second source of ionization having an importance at least comparable to that of the ultraviolet. The proton flux that would be required to provide a source of ionization strong enough to bring the computed electron densities into agreement with observation is calculated, and a comparison of these flux values with those typical of the solar wind shows that the solar wind is a potentially important ionization source for the Mars and Venus upper atmospheres. A quantitative treatment of solar wind flow across the planetary bow shock and the subsequent ionization produced will be necessary before its actual importance can be established.

1. Introduction

Calculations of the electron density profiles to be expected in the Mars and Venus ionospheres have been carried out for conditions corresponding to the Mariner 4, 5, 6 and 7 occultations. These calculations reveal serious discrepancies of up to a factor of 2 between theoretical and observed electron densities for all the Mariner flights, the observed electron densities being greater in each case. Several possible reasons for these discrepancies will be discussed below, but it appears that no completely satisfactory resolution of the difficulty can be obtained at present.

The extreme ultraviolet (EUV) fluxes used in this study are principally those tabulated by Hall and Hinteregger (1970). These data cover the spectral region from 270–1310Å and were obtained in March 1967 from a UV spectrometer aboard the OSO 3 satellite. For several reasons cited by the experimenters (the lack of any need to correct for atmospheric absorption, the low levels of scattered light exhibited by the instrument, and the longer periods of observation), these results should be superior to those obtained in 1963 from a rocket flight above White Sands, N. Mex. (Hinteregger *et al.*, 1965). The surprising feature of these two sets of UV fluxes is that the earlier values, which were obtained at a time of low solar activity (daily average 10.7-cm flux $F=76.0\times10^{-22}$ W m^{-2} Hz^{-1}), are generally higher than the later values obtained at a time of intermediate solar activity ($F=141.6\times10^{-22}$ W m^{-2} Hz^{-1}). Hall and Hinteregger state, however, that their 1967 data are consistent with UV data obtained from rocket flights made subsequent to the 1963 flight and they believe the earlier results were "systematically too large." The data of Timothy and Timothy (1970) are used to obtain the flux in the He II 304Å line while the data of Hall *et al.* (1969) are used to obtain fluxes in the various ultraviolet lines tabulated by these authors (except He II). For wavelengths <270Å the earlier tabulation of Hinteregger *et al.* (1965) is used.

All the calculations reported here have been carried out for a pure CO_2 neutral composition. More realistic neutral models based on the results of the Mariner 6 and 7 UV spectrometer experiment (Thomas, 1971) have been considered, but will not be discussed in this paper. It is found that although the ionic components of the ionosphere are radically changed in these models the magnitude of the calculated electron densities does not change greatly. Since the discussion and conclusions given in this paper would not be altered by using a more complex neutral composition, the pure CO_2 models are adequate for the present analysis.

For purposes of this study, model temperature profiles have been assumed rather than calculated. These profiles are specified in the thermosphere by a functional form

$$T(z)=T_m+(T_\infty-T_m)\{1-\exp[-(z-z_m)/C]\}, \quad (1)$$

where T_m, T_∞ and C are chosen to secure agreement between the altitudes of observed and calculated electron densities and between observed and calculated topside plasma scale heights. The exospheric temperatures chosen for the Mariner 4, 5, 6 and 7 models are 270, 650, 375 and 390K, respectively.

2. Results

The discrepancy between observed (Kliore *et al.*, 1965) and calculated electron densities for the Mariner 4 flight is shown in Fig. 1. The Mariner 4 occultation

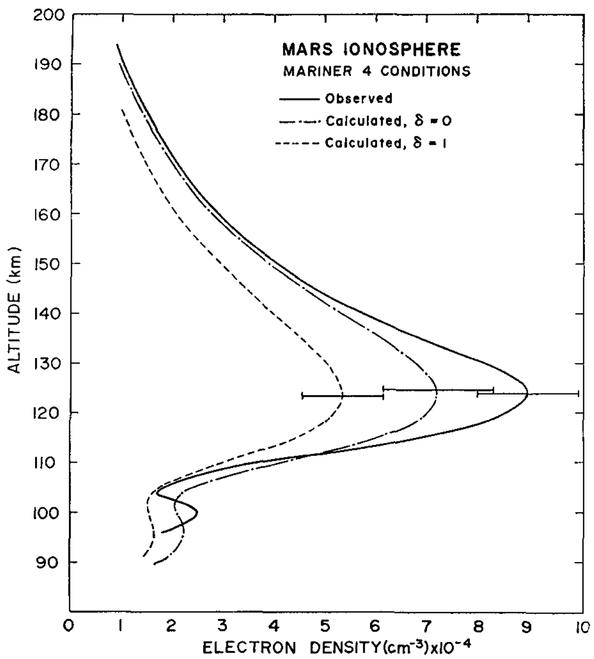

FIG. 1. Observed and calculated electron densities for Mariner 4 conditions. The two calculated profiles are obtained by scaling the solar flux data for intermediate solar activity to solar minimum conditions assuming a zero-to-one and one-to-one variation in EUV to 10.7-cm flux. See text for a discussion of the error bars.

occurred at a time of low solar activity and it is not certain how the EUV flux values of Hall and Hinteregger (1970), which are appropriate for intermediate solar activity, should be corrected. In a previous study concerned with variations in the Mars and Venus upper atmospheres over a solar cycle (Stewart and Hogan, 1969) a one-to-one variation in solar extreme ultraviolet to solar decimeter flux (five-month averages) was assumed, but it now appears that a milder variation in EUV actually occurs (Hall and Hinteregger, 1970; Hall *et al.*, 1969). The two computed electron density profiles of Fig. 1 result from assuming variations δ in EUV to 10.7-cm flux of zero-to-one and one-to-one ($\delta=0$ and 1, respectively). We see that even for the extreme assumption of no change in UV flux the computed densities are too low by 20% although the error bars on the experimental and theoretical curves do overlap in this case. The error bars on the experimental profile are based on the estimate of Kliore *et al.* (1965) and the method of deducing error bars for the theoretical curves will be discussed below. The estimate of an overall 0.5–1 variation in EUV to decimeter flux is probably realistic, and for this assumption the calculated electron density would be 30% too low.

Observed (Kliore *et al.*, 1967) and calculated electron densities for the Venus ionosphere are shown in Fig. 2. The observations were made by Mariner 5 at a time of intermediate solar activity, and only a slight correction (assuming $\delta=0.5$) is made to the flux values of Hall and Hinteregger. A similar small solar activity correction is made in the Mariner 6 and 7 calculations described below. The curve labeled $F_{\odot}$ is the electron density profile computed using the fluxes of Hall and Hinteregger while the curve labeled $4F_{\odot}$ was obtained by multiplying these fluxes by 4. Throughout the region of the major electron density maxima in the Mars and Venus ionospheres CO_2^+ is the principal ion produced, and the rate-limiting loss process is dissociative recombination of a product ion. These major peaks are thus Chapman layers, and the electron density is given approximately by the square root of the ratio of the electron production rate to the recombination coefficient. The factor of 2 discrepancy between observed and calculated electron densities in the Venus ionospheres therefore implies a factor of 4 error in the ratio of EUV flux to recombination coefficient as illustrated by the $4F_{\odot}$ curve in Fig. 2. The error bars on the observed profile are from the estimate of Kliore *et.al.* (1967) and that on the $F_{\odot}$ and $4F_{\odot}$ theoretical curves will be discussed below.

The Mariner 6 and 7 flights provided observations of the Martian ionosphere at a time of intermediate solar activity. Again, there is a large discrepancy between observed and calculated electron densities as indicated in Fig. 3. The observed profiles and their error bars are those obtained by Stewart and Hogan (1972) from their analysis of the radio occulation data. For these cases there is also a discrepancy of about a factor of 2 between observed and calculated electron densities. The curves labeled $4F_{\odot}$, as before, are electron densities obtained by arbitrarily multiplying the solar fluxes by 4. The neutral density and temperature profiles are held fixed for each model and only the effect on the ionosphere is considered for different solar fluxes.

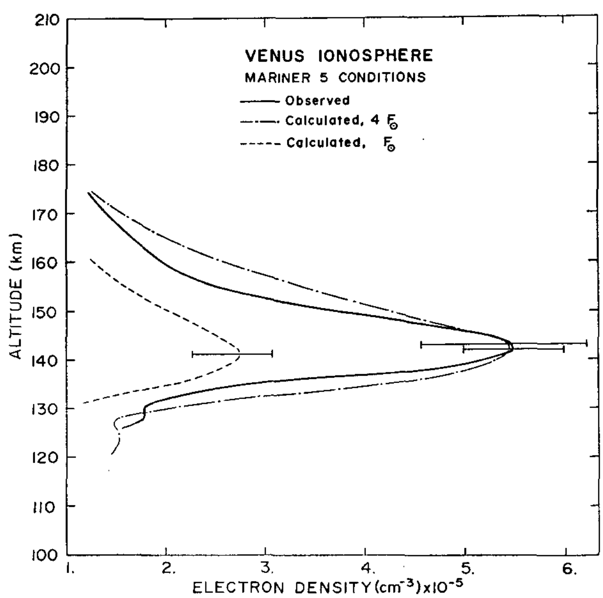

FIG. 2. Observed and calculated electron densities for the Venuionosphere under Mariner 5 conditions. The two calculated pros files are obtained by using measured solar fluxes directly ($F_{\odot}$) and by arbitrarily multiplying these fluxes by four ($4F_{\odot}$). See text for a discussion of the error bars.

3. Discussion

There are several potential sources for the discrepancies shown in Figs. 1–3: errors in the experimental measurements of UV fluxes and/or ionic recombination coefficients, unusually high levels of solar UV flux at the times of the Mariner occulations, errors in the assumptions upon which these calculations are based, and the presence of a source of ionization in addition to UV radiation.

Hall and Hinteregger (1970) estimate an accuracy of $\sim 20\%$ for their strong line and continua measurements with sums of weaker features over various wavelength intervals subject to errors of up to a factor of 2. If there is as much as 3% atomic oxygen at the altitude of the $F1$ peak on Mars as indicated by the Mariner 6 and 7 UV spectrometers (Thomas, 1971), then most of the CO_2^+ ions produced by solar ultraviolet radiation will be converted to O_2^+ ions via the interchange reaction $O+CO_2^+ \rightarrow CO+O_2^+$ (Fehsenfeld *et al.*, 1970). The most likely dominant ion throughout much of the Martian (and possibly Cytherean) ionosphere is, therefore, O_2^+.

The dissociative recombination coefficient for this ion has been measured by several investigators (Smith and Goodall, 1968; Biondi, 1969). The agreement among these various experiments, as well as the error limits given by the experimenters themselves, suggests that $\alpha_{O_2^+}$ is probably known accurately to within 20% over the temperature range of importance in the Mars and Venus ionospheres.

If we interpret the error limits given by the experimenters for the solar flux and recombination coefficient measurements as fractional standard deviations and write the electron density as

$$n_e = (Q/\alpha)^{\frac{1}{2}}, \tag{2}$$

then the fractional standard deviation in electron density resulting from these errors, S_{n_e}, is

$$S_{n_e} = [(\tfrac{1}{2})^2 S_Q^2 + (\tfrac{1}{2})^2 S_\alpha^2]^{\frac{1}{2}}, \tag{3}$$

according to the standard method for combining independent errors (Beers, 1957). In Eq. (3) S_Q and S_α are the fractional standard deviations in solar UV flux and recombination coefficient, respectively. Using a value of 0.2 for each, we find

$$S_{n_e} = 0.14. \tag{4}$$

The stated errors of measurement in UV flux and O_2^+ recombination coefficient thus permit an estimate of error limits of $\sim 15\%$ on computed electron densities and these are plotted on the various theoretical profiles of Figs. 1–3. This error is inadequate to account for a factor of 2 discrepancy between theory and observation. It is, of course, implicit in this discussion that the $\alpha_{O_2^+}$ measured in the laboratory is appropriate for ionospheric calculations.

One of the greatest difficulties in attempting to construct either thermal structure or ionospheric models

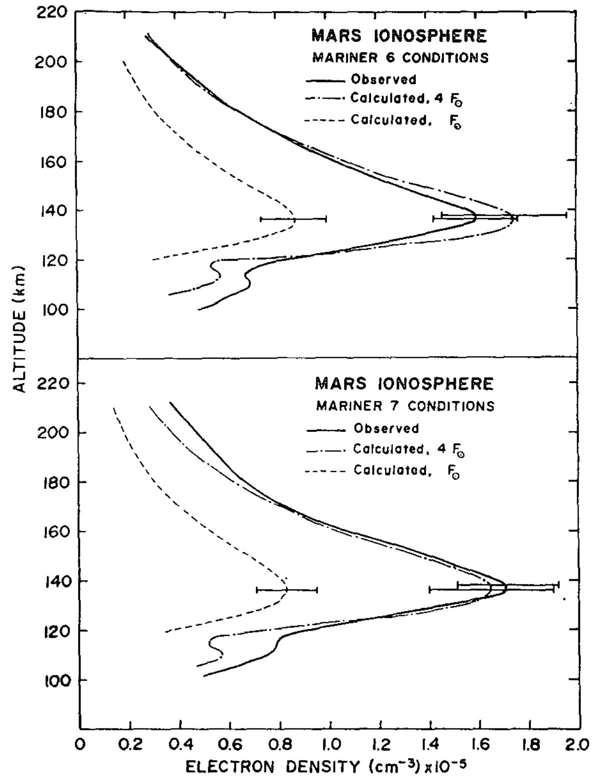

FIG. 3. Observed and calculated electron densities for the Martian ionosphere under Mariner 6 and 7 conditions. The two calculated profiles in each case are obtained by using measured solar fluxes directly ($F_\odot$) and by arbitrarily multiplying these fluxes by four ($4F_\odot$). See text for a discussion of the error bars.

of the Mars and Venus upper atmospheres to compare with the results of the Mariner experiments is that the solar UV fluxes are not measured at the times of the fly-bys but must be extrapolated from the time at which measurements are made. The usual procedure is to use variations in five-month averages of the solar 10.7-cm flux as an indicator of variations in the solar EUV, but the degree to which the two fluxes are correlated is not well established. We might postulate elevated levels of solar UV flux at the times of the various Mariner encounters as a resolution of the difference between observed and computed electron densities, and in view of the fact that the EUV fluxes at these times are unknown this cannot be directly disproved. There is considerable indirect evidence against such an assumption, however. There is nothing in the observed indicators of solar activity, such as the five-month average and daily value of 10.7-cm flux, to support the postulate of enhanced EUV flux during the Mariner encounters. Table 1 lists the monthly average, $\bar{F}$, and daily, F, values of 10.7-cm flux at the times of the various Mariner encounters as well as the density residuals obtained from earth satellite drag data. The 10.7-cm flux values are from *Solar-Geophysical Data* (U. S. Dept. of Commerce) and the satellite data were provided by J. Levine (1971, private communication). The drag on

TABLE 1. Indicators of solar activity (10.7-cm flux: W m^{-2} Hz$^{-1}\times10^{22}$) at the times of the various Mariner encounters where $\bar{F}$ is the five-month average of this flux about the encounter times and F the daily value for the encounters.

Flight	10.7-cm flux $\bar{F}$	F	Earth satellite drag data Satellites	Density residuals
Mariner 4, Mars	78.0	74.5	Explorer 9, 24	near zero
Mariner 5, Venus	145.2	119.3	Explorer 19, 24	near zero
Mariner 6, Mars	148.5	167.0	Explorer 19, 39	large negative
Mariner 7, Mars	149.3	187.7	Explorer 19, 39	near zero

earth-orbiting satellites during the Mariner encounter period also shows no unusual increases in upper atmosphere density as would be expected during times of increased EUV flux. Such increases in upper atmosphere density would result in a large positive density residual (difference between observed and predicted density), and, as Table 1 indicates, no such positive residuals were observed during any of the Mariner encounter periods. It is of interest to note that the large negative density residuals indicated in Table 1 could reflect a somewhat reduced level of solar activity during the Mariner 6 encounter period. The 10.7-cm flux values for 31 July and 5 August 1969 also suggest a higher level of solar activity during the latter (Mariner 7 encounter) period. The observed electron densities are consistent with this picture. The Mariner 7 peak density of 1.7×10^5 cm^{-3} sec^{-1} suggests about a 14% increase in the ionization source between Mariner 6 and 7 occultations.

The agreement between the theoretical and observed plasma scale heights exhibited for the Mars and Venus ionospheres in Figs. 1–3 indicates that the discrepancy in the magnitude of the electron densities does not result from large errors in the thermal structure models if strict photochemical equilibrium is granted. In a Chapman layer the maximum electron density is inversely proportional to the temperature at the ionization peak and if the factor of 2 error in electron density were attributed to the thermal structure model it would imply a factor of 2 error in temperature at the F_1 peak. Any attempt to adjust parameters in the thermal structure models to secure agreement between observed and calculated electron densities at the F_1 peak would destroy the agreement in the plasma scale heights.

The calculated electron density profiles shown in Figs. 1–3 are based on the assumption of photochemical equilibrium and it seems unlikely that this assumption can be seriously in error over most of the altitude range covered by the observations. However, the solar wind interaction model proposed for the Martian ionosphere by Cloutier *et al.* (1969) would alleviate the discrepancy between calculated and observed electron densities in two ways: 1) the ionization carried from higher to lower altitudes would increase the electron density at the F_1 maximum; and 2) the higher thermospheric temperatures in this model would result in a decreased recombination coefficient $\alpha_{O_2^+}$ and thus in higher electron densities. However, the Martian exospheric temperatures predicted by this model are not compatible with the results of the Mariner 6 and 7 UV spectrometer experiment (Stewart, 1971), and since the model does not alleviate the discrepancy in the Venus ionosphere it is not an attractive alternative.

In view of the above arguments it seems unlikely that the discrepancy between observed and calculated electron densities in the Mars and Venus ionospheres reflect errors either in the measured physical quantities entering into the calculations or in the basic assumptions underlying the thermal structure model upon which these calculations are based. The existence of an additional source of ionization thus seems the most likely explanation at present, but whether or not the solar wind can provide such a source bears further investigation.

Several authors have considered the possibility that the solar wind provides a significant source of ionization for the Mars and Venus ionospheres (Shimizu, 1964; Walker and Sagan, 1966; Sagan and Veverka, 1967; Whitten, 1970). Most of these authors assume direct penetration of the solar wind into the planetary upper atmosphere, and none treat the problem of plasma transport across the shock which will form above the F1 maximum in the planetary ionosphere. The formation of a bow shock will tend to divert the solar wind plasma flow around the planet and thus reduce the effectiveness of solar wind penetration into the ionosphere. The assumption of direct flow into the atmosphere provides an estimate of the maximum effectiveness of solar wind ionization in the Mars and Venus ionospheres.

Table 2 shows in the second column the calculated photoproduction rates at the F1 peak for the various theoretical electron density profiles in Figs. 1–3. The Mariner 4 electron density profile corresponding to the photoproduction rate of Table 2 is not actually exhibited in Fig. 1, but is calculated under the assumption that $\delta=0.5$. The other photoproduction rates correspond to the $F_\odot$ profiles of Figs. 2 and 3. The third column shows the production rate that would be required at the F1 peak to match the observed electron density, and the fourth column gives the source function deficit, i.e., the difference of columns two and three. The last column gives the factor by which the fluxes tabulated

TABLE 2. Calculated and observationally required ionization sources at the F1 peaks in the Mars and Venus ionospheres.

Flight	Calculated source $F_\odot$ (ions cm^{-3} sec^{-1})	Required source (ions cm^{-3} sec^{-1})	Source deficit (ions cm^{-3} sec^{-1})	Required proton flux at 1 A.U. (cm^{-2} sec^{-1})	Required EUV*
Mariner 4	1.2×10^3	2.4×10^3	1.2×10^3	1.6×10^8	2.0
Mariner 5	2.8×10^4	11.5×10^4	8.7×10^4	9.6×10^8	4.1
Mariner 6	2.9×10^3	9.9×10^3	7.0×10^3	6.8×10^8	3.4
Mariner 7	2.6×10^3	11.2×10^3	8.6×10^3	9.4×10^8	4.3

* Factor by which calculated fluxes $F_\odot$ would have to be multiplied to give agreement with the observed profiles.

by Hall and Hinteregger (1970) would have to be multiplied to give agreement between the observed and calculated profiles.

Column five gives the proton flux, normalized to 1 A.U., that would be required if the additional ionization were attributed to direct penetration of solar wind protons into the Mars and Venus ionospheres. It is assumed that these fluxes have the energy spectrum utilized by Walker and Sagan (1966) and Sagan and Veverka (1967) which is based on the Mariner 2 data of Neugebauer and Snyder (1966) and that 34 eV are required for each ion pair produced. The column ionization rate (ions cm^{-2} sec^{-1}) is then readily computed and the ion production at the F1 peak obtained by dividing the column rate by the local scale height. This assumes that the solar proton ionization will occur at the same altitude as that due to EUV. This assumption is supported by the calculations of Walker and Sagan (1966) and Sagan and Veverka (1967). It is also assumed that the solar wind flows radially outward from the sun and the solar zenith angles appropriate to the various Mariner encounters are taken into account in the column ionization rates.

The required proton fluxes listed in Table 2 are within the range of values actually observed (Brandt, 1970). The flux of 1.6×10^8 cm^{-2} sec^{-1} required to produce the observed ionization in the Mariner 4 case is reasonable for quiet solar conditions, but the fluxes required for the Mariner 5, 6 and 7 cases are higher than average solar wind conditions. Since only the proton component has been considered, these magnitude estimates do not rule out the possibility that solar wind ionization could account for the observed electron densities on Mars and Venus, and it is clear that a detailed analysis of the solar wind flow across the planetary bow shock is required to substantiate or refute this mechanism.

The energy fluxes at the tops of the Mars and Venus atmospheres implied by the proton fluxes listed in Table 2 are 0.19, 4.1, 0.75 and 1.0 erg cm^{-2} sec^{-1} for the Mariner 4, 5, 6 and 7 flights, respectively. The corresponding energy fluxes of ionizing radiation calculated from the data of Hall and Hinteregger (1970) are 0.37, 2.7, 0.71 and 0.71 erg cm^{-2} sec^{-1}. Thus, with the exception of the Mariner 4 flights which occurred near solar minimum, the solar wind energy input into the Mars and Venus upper atmospheres would have to exceed that due to ionizing UV radiation to account for the observed electron densities. In the Martian upper atmosphere both the neutral scale heights derived from the Mariner 6 and 7 UV spectrometer data (Stewart, 1971) and the plasma scale height derived from the radio occultation data (Hogan *et al.*, 1971) imply exospheric temperatures $\leqslant 450K$. The heating efficiency of the solar wind, like that of the ionizing ultraviolet, must be quite low. Therefore, if the solar wind proves an important source of ionization in the Mars and Venus ionospheres, it must also be an important source of airglow excitation that will have to be considered in analyses of UV spectrometer results.

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